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RESEARCH MEMORANDUM

PRELIMINARY EXPERIMENTS ON THE ELASTIC COMPRESSIVE

BUCKLING OF PLATES WITH INTEGRAL

WAFFLE-LIKE STIFFENING

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SUMMARY

An experimental investigation was made of the elastic compressive buckling strength of plates having various configurations of integral stiffening. Configurations tested included ribbing that was longitudinal, transverse, longitudinal and transverse, and skewed at various angles to the sides of the plates to form a diamond or waffle-like pattern. The 45° waffle stiffening was found to be the most effective of all those considered, giving a buckling load nearly double that for the same waffle pattern with the ribbing longitudinal and transverse.

INTRODUCTION

The great merit of integral stiffening, both from the standpoint of reducing costs of airframe construction and from the standpoint of increasing structural efficiency, has been pointed out by several authors (refs. 1, 2, and 3). The most common form considered for the stiffening has been longitudinal or transverse ribbing extruded (ref. 4), rolled (ref. 5), or milled (ref. 6) integrally with the skin.

The advent of the large forging press (ref. 7) makes possible the production of integrally stiffened sheet having stiffening configurations more complicated than simple longitudinal or transverse ribbing. The disadvantage of simple longitudinal or transverse ribbing is that it provides high bending stiffness in only the longitudinal or the transverse direction. Inasmuch as the buckling strength of a plate depends upon both longitudinal and transverse bending stiffnesses, and also upon the twisting stiffness, a more effective stiffening arrangement would appear to be one which would raise all three stiffnesses simultaneously. In the present study the elastic compressible buckling strengths of plates having several arrangements of integral stiffening

were studied experimentally. The stiffening arrangements considered
included longitudinal ribbing, transverse ribbing, and two-way waffle-
like ribbing - both longitudinally and transversely, and skewed at
various angles to the sides of the plates to form a diamond pattern
(see fig. 1). Skewing the stiffening from the longitudinal direction
tends to raise the transverse bending stiffness and the twisting stiff-
ness. Skewed integral stiffening of this type has been named
"isogonigral" (isogonic plus integral) stiffening.

SYMBOLS

H over-all height of stiffening plus skin, in.

t_S thickness of skin, in.

$\bar{t}$ thickness of solid plate of same weight as stiffened plate, in.

W width of plate, in.

σ_{cr} critical stress, ksi

TEST SPECIMENS AND PROCEDURE

The integrally stiffened plates used in this investigation were
made up as sand castings of 355 aluminum alloy, heat treated, and aged
to the T61 condition. The castings were machined down to the desired
thicknesses and riveted together into square tube test specimens using
$1/16 \times 1/2 \times 1/2$-inch corner angles of 24S-T4 aluminum alloy and
3/32 inch diameter A17S-T4 aluminum-alloy universal head rivets at
approximately 1/2-inch pitch. Eight configurations of integral stiff-
ening and two specimens of each configuration were used (see fig. 1),
namely, longitudinal ribbing, two-way ribbing at 15°, 30°, 45°, 60°,
and 75° to the longitudinal axis of the specimen, transverse ribbing,
and longitudinal and transverse ribbing. The proportions of the ribbing
were chosen after consultations with several manufacturers of press
forgings to be in the range that might be manufactured by current
forging practice. On all specimens the nominal rib cross-sectional
dimensions were the same (see fig. 2) and the rib spacing (1/2 inch on
the longitudinally or transversely stiffened plates, 1 inch on all
others) was such as to keep the ribbing material approximately equal in
weight to sheet 0.050 inch thick. Also on all specimens, except in the
final series of tests in which the skin thickness was varied, the nominal
skin thickness t_S was 0.050 inch.

The square tube test specimens were designed to buckle in compression at low stresses in order not to exceed the elastic range of the cast material. The tubes were approximately 10 inches wide by 45 inches long. Square tubes of constant wall thickness having the same material and weight as the test specimens would buckle (as long simply supported flat plates, see ref. 8) in the stress range from 3.8 ksi to 5.0 ksi, the variation being due to the differences in widths and thicknesses of the various configurations. This stress range was believed low enough to insure that the proportional limit would not be exceeded even if the stiffening raised the buckling stress very appreciably. Actually, because the buckling loads achieved by some of the integrally stiffened specimens were somewhat higher than anticipated, the proportional limit was exceeded in some cases. Inasmuch as the maximum corner strain measured for any specimen at buckling was only 0.002, however, reference to the stress-strain curve of figure 3 reveals that the plastic action at most was very small.

The specimens were compressed flat ended in the 1,200,000 pound testing machine in the Langley structures research laboratory. Buckling was detected by "buckle-bars" resting against the sides of the tubes to detect lateral deflections as was done in reference 9, and the buckling load was determined as the "top-of-the-knee" of the curve of plate deflection against load plotted autographically from the buckle-bars. A well defined buckling load was obtained in this manner for all except the longitudinally stiffened specimens and the specimens with 45° waffle-like stiffening and a nominal skin thickness of 0.075 inch. The longitudinally stiffened specimens bowed slightly as soon as load was applied; the top-of-the-knee was here accordingly rather vaguely defined and an error in the determination of the average buckling load for these specimens of as much as 20 percent of the load is believed possible. The buckling of both of the specimens with 45° stiffening and 0.075 inch skin was accompanied by failures in the rivets with which the tubes were assembled; the buckling load for at least one of these two specimens was undoubtedly caused to be too low owing to inadequate riveting, although no evidence of inadequate riveting was observed on any of the other specimens. The errors in the buckling loads for all the other specimens are believed to be less than 10 percent of the average of the test values for the two specimens of each configuration.

RESULTS

Three series of test results are presented in table 1 and figures 4, 5, and 6. In the first series, the relative merits of longitudinal, transverse, and longitudinal and transverse ribbing are considered; in the second skewed stiffening and in the third a variation in skin thickness are investigated.

Longitudinal, transverse, and longitudinal and transverse ribbing.-
The buckling load for the longitudinally stiffened plates composing the
four sides of the square tube test specimen was found to average only
17 percent higher (see fig. 4) than that calculated for four simply
supported flat plates of equal size and weight. The buckling loads for
the transversely stiffened plates averaged less than that for unstiff-
ened plates of equal weight. In the case of both longitudinal and
transverse stiffening (with only half as many longitudinal and half as
many transverse ribs as the plates with one way stiffening so that the
weight of stiffening was the same) the buckling loads averaged appreci-
ably higher, reaching 184 percent of the buckling load of equal weight
flat plates.

Skewed (isogonigral) stiffening.- The buckling loads for the speci-
mens with skewed stiffening increased with the angle of skew to a maxi-
mum at an angle of 45° (see fig. 5). The buckling loads for the plates
with 45° waffle-like stiffening averaged 309 percent of that of equal
weight unstiffened flat plates.

45° waffle-like (isogonigral) stiffening on skin of various thick-
nesses.- The ratio of buckling loads for specimens with 45° waffle-like
stiffening to those for equal weight solid plates increased as the skin
thickness decreased. The maximum ratio of rib height $(H - t_S)$ to skin
thickness investigated was approximately 5 and at this ratio the buck-
ling loads averaged 432 percent of that for equal weight unstiffened
flat plates (see fig. 6).

DISCUSSION

For providing resistance to the compressive buckling of a long,
simply supported flat plate in the elastic range, the 45° waffle-like
stiffening was by far the most effective of all the configurations
investigated. Buckling loads of more than three times those of unstiff-
ened plates of equal weight were attained at this angular orientation
with the relatively shallow ribbing used. One way ribbing of the same
cross section, either longitudinally or transversely, was little or no
better than no stiffening at all. A plate with equivalent two-way
stiffening, (longitudinal and transverse) while more effective than one
with stiffening only longitudinally or transversely, still buckled at
little more than one-half the load that it would have achieved with its
ribbing skewed at 45° to the longitudinal and transverse axes.

While these results show the 45° angle to be the optimum for a long
plate in compression in the elastic stress range, the optimum angle can
be expected to vary somewhat for plates of other aspect ratios or
subjected to other loading conditions. For short plates (which buckle

like columns) the optimum angle may be less than 45°; reducing the angle
below 45° raises the longitudinal bending stiffness and hence the column
strength. For narrow plates (which buckle well up in the plastic range
in compression), again the optimum may be less than 45°; here reducing
the angle allows the ribbing to pick up more of the load and hence to
delay the onset of plastic action in the sheet. For long plates in
shear in the elastic stress range, reference 10 suggests that the
optimum may be produced by a ribbing pattern which forms a square grid
like the 45° ribbing but has the axes of principal stiffness skewed at
slightly more or slightly less than 45° depending upon the direction of
shear. For shear in the plastic range, on the other hand, the 45° angle
(which allows the ribbing to pick up the load directly) appears ideally
suited. Evidently 45° is not far from the optimum for a wide range of
applications - elastic compression, elastic or plastic shear, or combined
compression and shear in either the elastic or plastic range.

The proportions of the stiffening, chosen to conform to present
forging practice, which were used throughout this investigation, were
known to be far from the optimum from the standpoint of structural
efficiency. As indicated by the third series of tests, in which the
waffle stiffening was shown to become more efficient relative to equal
weight solid sheet as the ratio of rib height to skin thickness increased,
a deeper ribbing should be more effective for resisting buckling than that
used for the majority of the present tests. Just how effective integral
stiffening of any type can be depends upon the proportions which can be
produced.

The proportions of integral ribbing which can be forged success-
fully depend at least to some extent upon the final skin thickness to be
achieved between the ribs. The forging of ribbing of the proportions
used in this investigation, for example, would be easier on very thick
skin than on very thin skin; the minimum skin thickness on which such
ribbing can be forged can only be determined by trial. If thinner skins
are required than forging will permit, however, or if a taper in thick-
ness is desired, machining can be resorted to even as it is at present
in many cases for the production of tapered solid sheet.

The forging of sheets of any appreciable size with integral waffle-
like stiffening would require the largest forging presses available.
Quantity production of such waffle-stiffened sheet by rolling, however,
should not require such extravagant equipment. Attempts to roll such
sheet at the Langley Laboratory using 24S aluminum alloy and rather crude
equipment improvised from a plate bending roll have revealed no particular
difficulties. The rolling of ribbing, at least to the proportions of the
present investigation, using a smooth cylindrical roll and a flat die in
which the ribbing pattern is cut, appears relatively straightforward.

CONCLUDING REMARKS

The ultimate value of integral waffle-like stiffening will depend
upon how well it stands up at high stresses and how readily it lends
itself to fabrication. The preliminary results reported herein indicate
that waffle-like stiffening, particularly at or about the $45°$ angle, is
of sufficient structural interest to merit further study of the plastic
buckling and fabrication aspects.

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TABLE 1.- DIMENSIONS OF SQUARE TUBE TEST SPECIMENS AND TEST DATA

Stiffening arrangement (deg)	Skin thickness, t_S (in.)	Over-all thickness, H (in.)	Ratio of rib height to skin thickness, $\frac{H-t_S}{t_S}$	Plate width, W (in.) (a)	Length (in.)	Weight (lb) (b)	Volume (cu in.) (c)	Thickness of equivalent plate, $\bar{t}$ (in.) (d)	Buckling stress, equivalent plate, σ_{cr} (ksi) (e)	Buckling load equivalent tube (kips) (f)	Measured buckling load (kips)	Ratio of measured to equivalent tube buckling load
0 0	0.053 .039	0.255 .246	3.81 5.31	10.1 10.2	45.5 45.6	18.6 18.4	194 192	0.106 .103	4.31 3.99	19.5 17.8	20.8 22.5	1.07 1.26 1.17 av.
15 15	.060 .050	.257 .245	3.29 3.90	10.0 10.0	44.8 44.8	18.5 17.4	193 181	.108 .101	4.56 3.99	20.8 17.1	28.0 25.2	1.35 1.47 1.41 av.
30 30	.066 .055	.251 .249	2.80 3.53	10.2 10.2	44.8 45.1	18.5 18.4	193 192	.106 .104	4.22 4.07	19.2 18.3	42.7 39.8	2.22 2.18 2.20 av.
45 45	.038 .037	.224 .224	4.90 5.05	10.0 10.0	45.6 45.6	13.9 14.0	145 146	.080 .080	2.50 2.50	8.58 8.62	39.0 35.3	4.55 4.09 4.32 av.
45 45	.062 .056	.252 .247	3.07 3.41	10.0 10.0	45.3 45.6	17.5 17.6	182 183	.101 .101	3.99 3.99	17.1 17.1	51.7 54.0	3.02 3.16 3.09 av.
45 45	.071 .079	.271 .289	2.82 2.66	10.1 10.1	45.6 45.6	21.1 22.6	220 236	.119 .128	5.44 6.29	27.7 34.2	60.0 51.4	2.16 1.50 1.83 av.
45 45	.096 .101	.296 .296	2.08 1.93	10.1 10.1	45.6 45.6	26.0 26.1	271 272	.147 .148	8.29 8.40	51.4 52.1	75.0 78.0	1.46 1.50 1.48 av.
60 60	.057 .059	.248 .247	3.35 3.19	10.1 10.1	45.4 45.3	17.8 18.1	185 189	.101 .103	3.91 4.07	17.0 18.0	43.5 40.8	2.56 2.27 2.42 av.
75 75	.051 .049	.248 .245	3.86 4.00	9.75 9.75	44.3 44.3	16.2 16.1	169 168	.098 .097	3.95 3.87	16.1 15.7	28.0 26.4	1.74 1.68 1.71 av.
90 90	.044 .046	.245 .248	4.57 4.39	10.0 10.1	45.4 45.4	19.8 19.7	206 205	.113 .112	4.99 4.81	23.9 23.0	19.0 21.0	.79 .91 0.85 av.
0 + 90 0 + 90	.067 .061	.249 .250	2.72 3.10	10.1 10.1	45.2 45.2	19.5 18.2	203 190	.111 .104	4.72 4.15	22.4 18.4	39.5 35.4	1.76 1.92 1.84 av.

a Inside width of tube.

b Does not include weight of corner angles or rivet heads.

c Density of 355-T61 aluminum-alloy taken as 0.096 lb/cu in.

d Volume, divided by length times four times the width.

e Computed as $\sigma_{cr} = \dfrac{4\pi^2(10700)\bar{t}^2}{12(0.9)W^2}$.
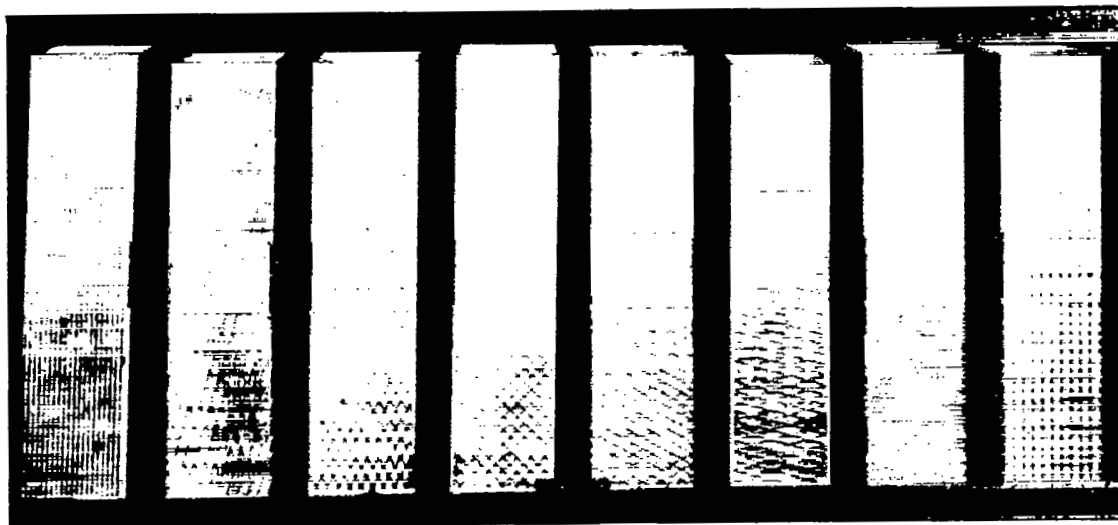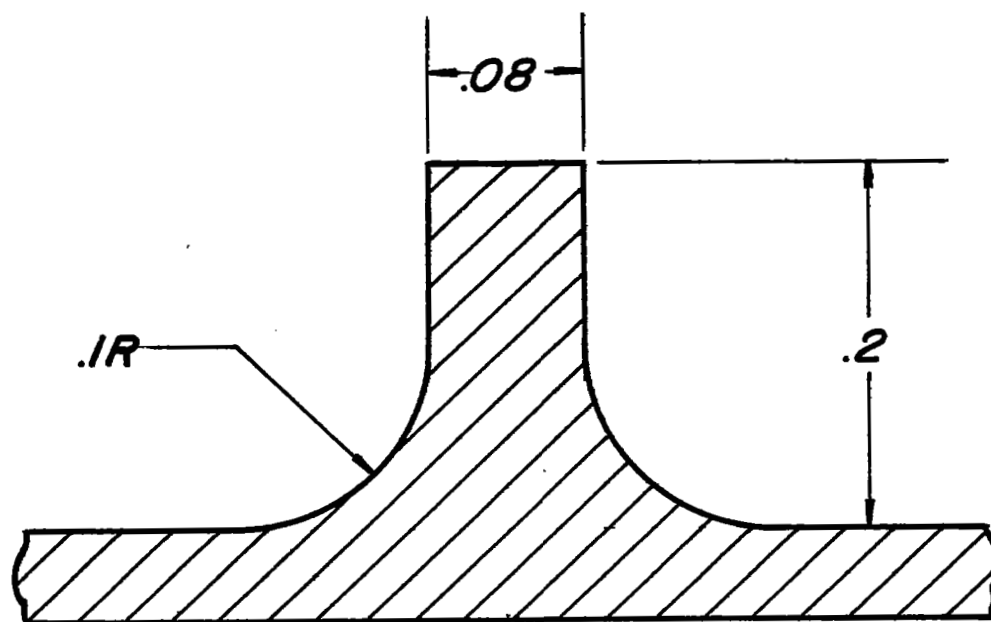
f Includes load carried by angles.

Figure 1.- Configurations of integral stiffening investigated. L-74130

Figure 2.- Cross section of ribbing used on all test specimens.
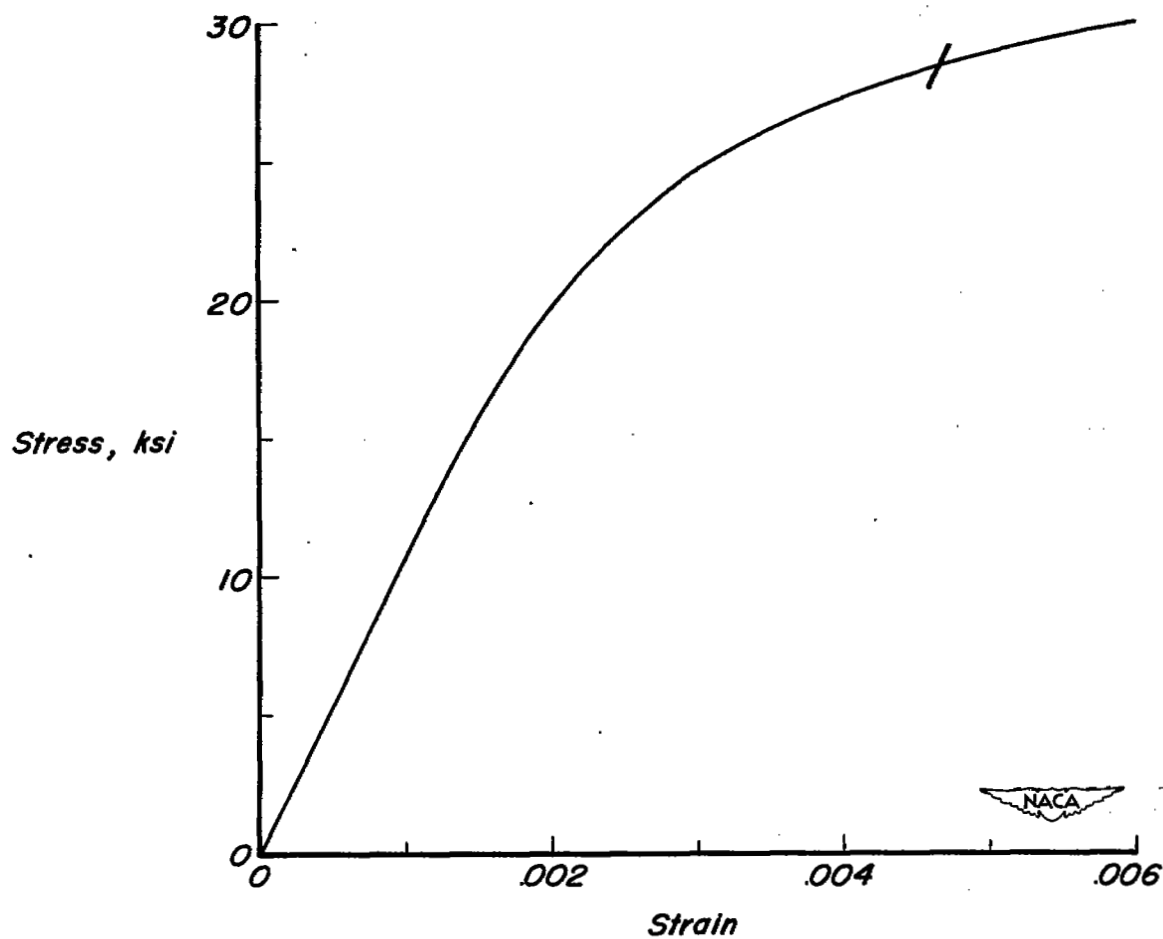
Figure 3.- Compressive stress-strain curve for the 355-T61 aluminum-
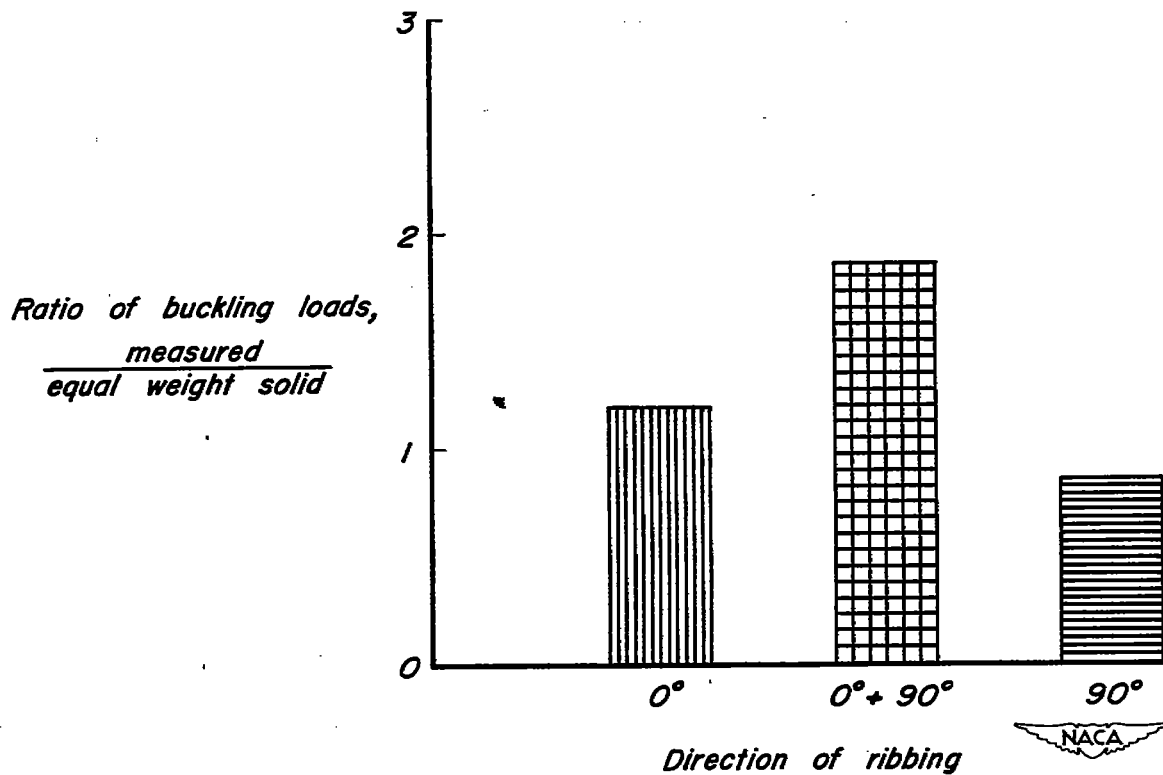alloy used for test specimens.

Figure 4.- Ratio of buckling loads measured for longitudinally,
transversely, and longitudinally and transversely stiffened
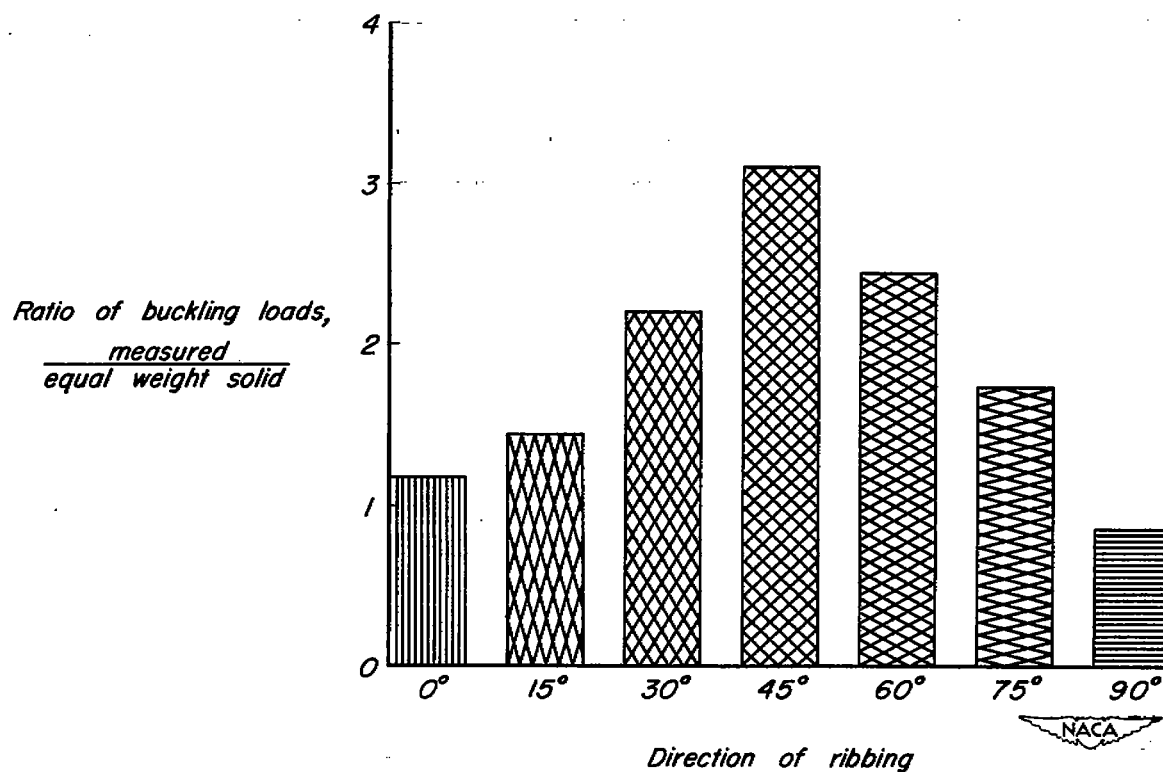test specimens to calculated buckling loads for flat plates
of equal weight.

Figure 5.- Ratio of buckling loads measured for specimens with skewed
    stiffening to the calculated buckling loads for flat plates of equal
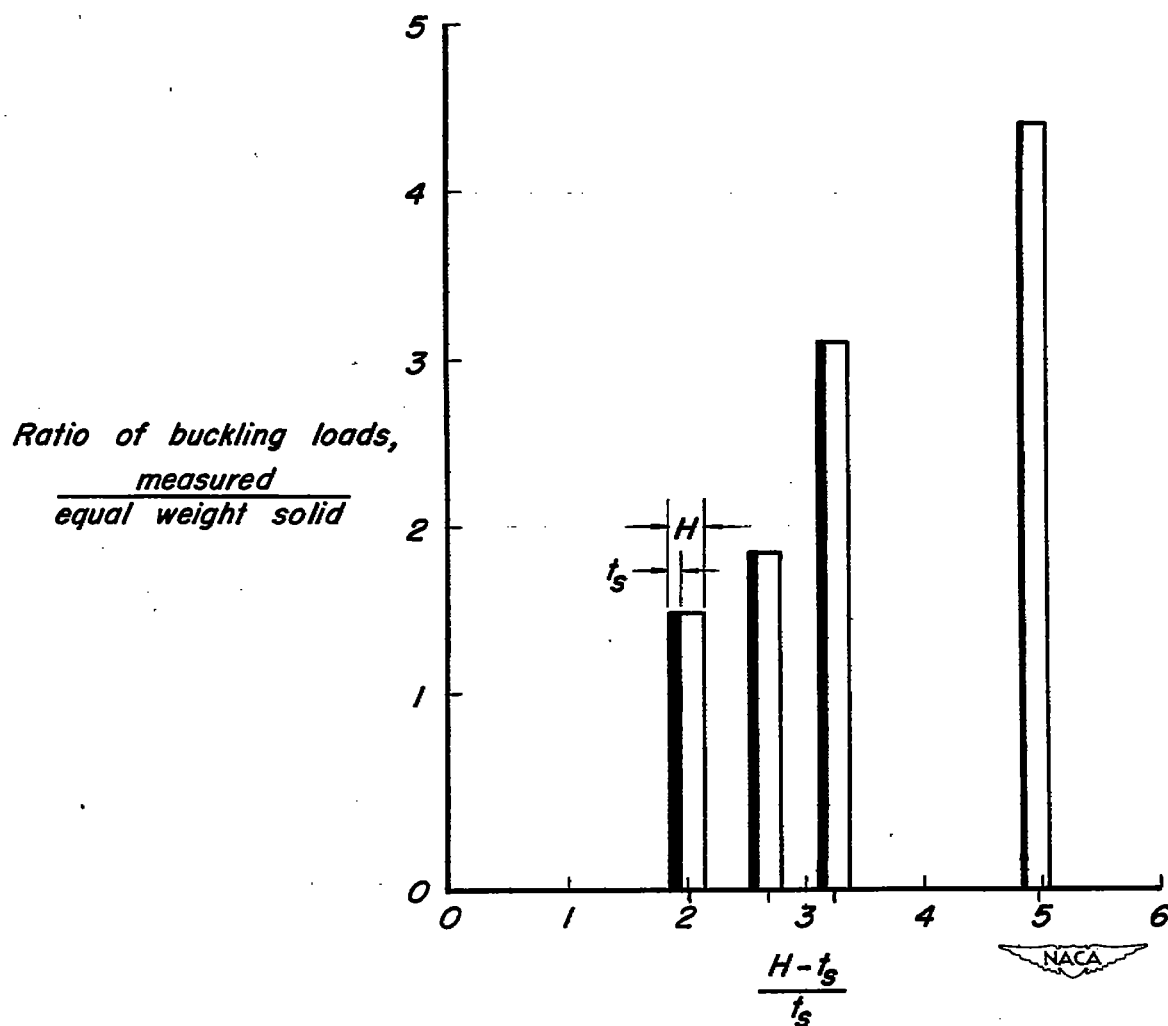   weight.

Figure 6.- Variation with changing skin thickness in ratio of measured
    buckling load to calculated buckling load for flat plate of equal
    weight for test specimen having 45° ribbing.